National Aeronautics and Space Administration

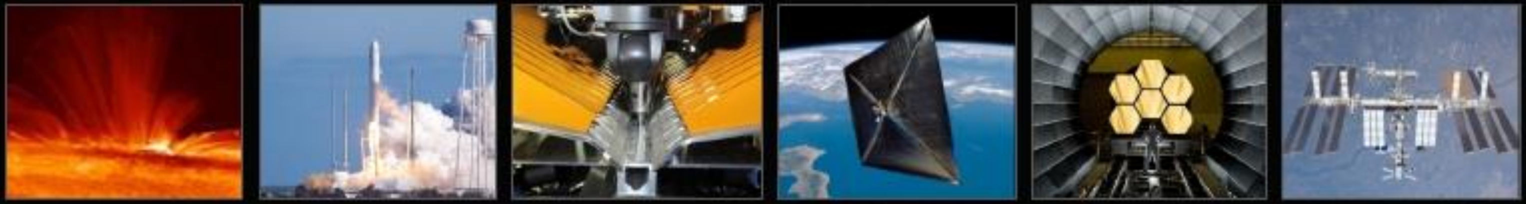
NASA In Space Manufacturing Vision for Extraterrestrial Environments

ASPSM Expeditionary On-Demand Manufacturing Workshop

January 21, 2016

Aberdeen Proving Grounds, MD

marshall



R.G. Clinton, Jr.

Deputy Manager, Science and Technology Office

Image courtesy of startrek.com

First 3D Printing Experiment in a Microgravity Environment

“Microgravity Manufacturing” on NASA’s KC-135 – Ken Cooper, MSFC,1999

- Fused Deposition Modeler (FDM) was flown aboard the NASA Reduced Gravity aircraft (KC-135) to determine the feasibility of using layer based manufacturing in a microgravity environment.
- General objectives were:
  1. To analyze the inter-layer bonding horizontally
  2. To assess overall dimensional stability of the specimens relative to the same designs fabricated in 1-g
  3. To determine the overall operability of an extrusion-based manufacturing process without the assist of gravity.
- Fabrication experiments were conducted on several specimen designs: horizontal tensile, thin wall vertical column, cantilever, bridge-and-piers, and dome
- General Conclusions and Final Analyses
  - The horizontal layers bonded well
  - The FDM operated properly
  - Dimensions of the flight parts were consistent with those of the ground parts
  - High humidity and multi-g segments of the flight test impacted the prints
  - **The application of layered fabrication techniques is apparently feasible for standard and some non-standard part designs.**

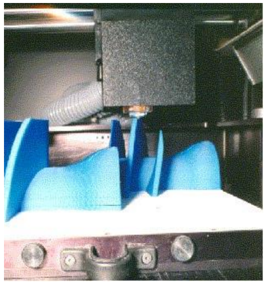
In Situ Fabrication and Repair (ISFR) Program Element

Office of Biological and Physical Research, 2005

FABRICATION

OF TOOLS AND PARTS WITH THE FOLLOWING EMPHASIS:

- *Feedstock flexibility (In Situ, provisioned, recycled)*
- *Miniaturization*
- *Speed*
- *Part accuracy ad surface finish*
- *Multi material*



Turbine

REPAIR

CAPABILITIES WITH THE FOLLOWING EMPHASIS:

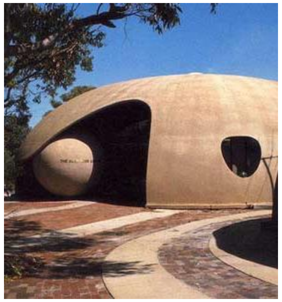
- *Unique material properties*
- *Environmental performance*
- *In Situ processes*

Welding

HABITAT STRUCTURES

CAPABILITIES WITH THE FOLLOWING EMPHASIS:

- *Radiation shielding features*
- *Use of In Situ resources*
- *Autonomous construction*



Inflatable Concrete Structure

NON DESTRUCTIVE EVALUATION

CAPABILITIES WITH THE FOLLOWING EMPHASIS:

- *Independent quality assurance of In Situ processes*
- *Integrated closed loop control of In situ process*
- *Failure analysis and routine inspection applicability*

Measuring Machine/ Laser Scan

RECYCLING

CAPABILITIES WITH THE FOLLOWING EMPHASIS:

- *Reuse of failed parts & waste materials*
- *Limitation of waste stream variety*
- *Simplification*

Reactor

SYSTEM OF SYSTEMS / APPLICABILITY AND CONSIDERATION:

- *Mobile Army Parts Hospital*
- *Interoperability between ISFR, FAB, REPAIR NDE, RECYCLING, and, HAB concepts*

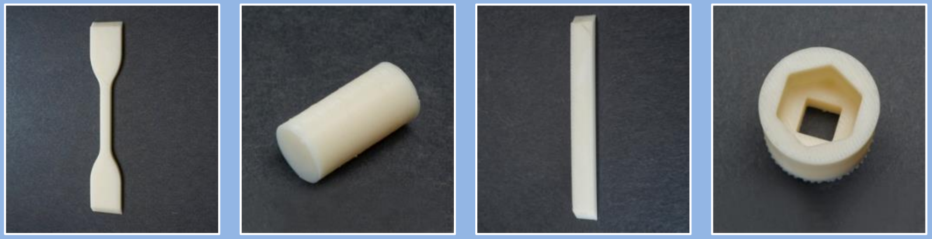
In Space Manufacturing: 3D Printing in Zero-G International Space Station Technology Demonstration, 2014


Microgravity Research


3D Print Ground Testing


3D Print in Micro-G Science Glovebox (MSG)

Mechanical Property Test Articles



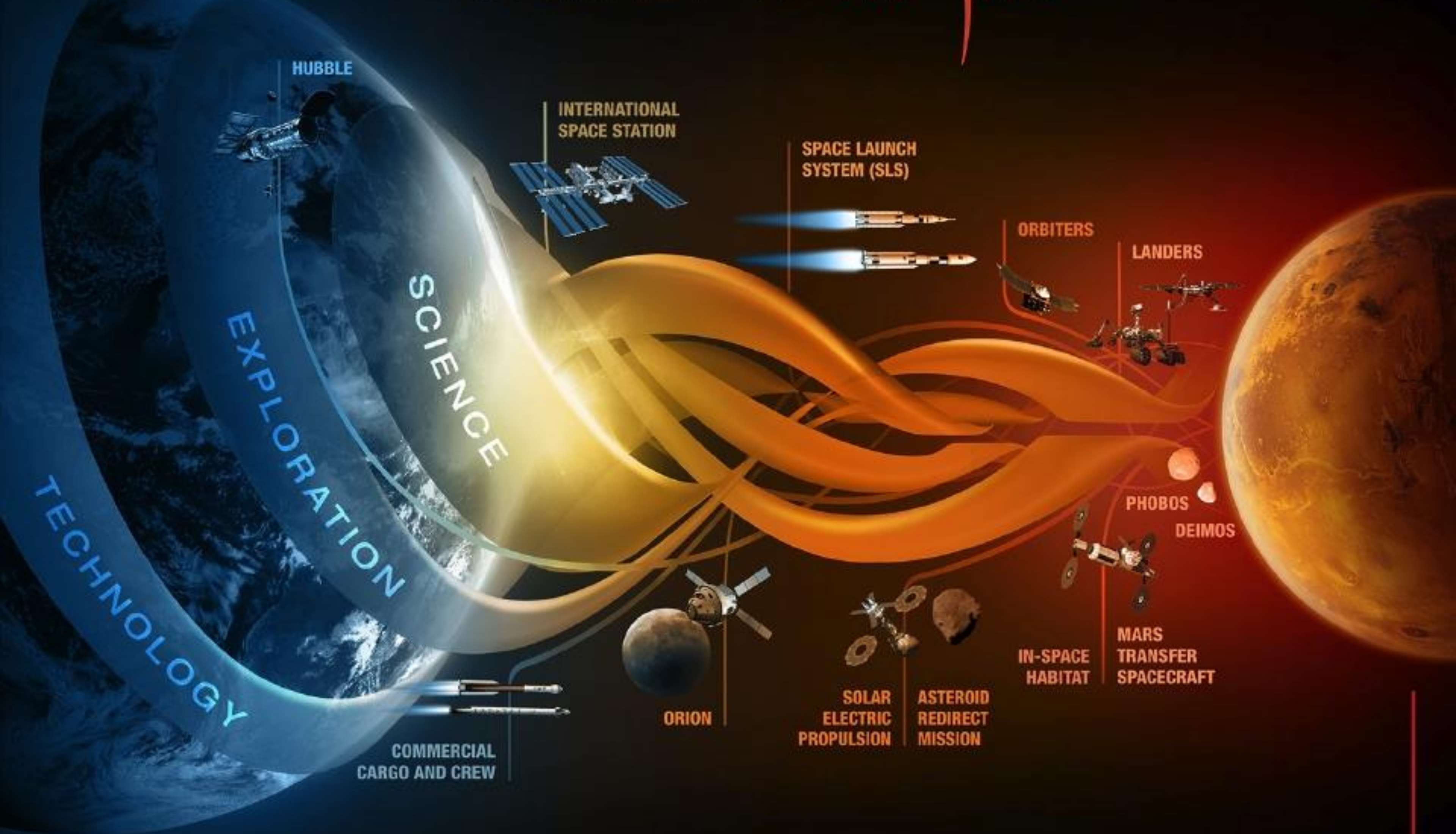
Functional Tools

3D Print ISS Technology Demonstration - Preliminary Results

Threshold Requirement: The In-Space Manufacturing (Former 3D Print) project shall produce 3D multi layer object(s) that generate data (operational parameters, dimensional control, mechanical properties) to enhance understanding of 3D printing process in space

- Ground Control Samples were printed prior to launch
- A total of 21 parts were printed on ISS, including the uplinked ratchet handle
- The 3D Printer performed flawlessly on ISS
- Inspection and testing of all articles included:
  - Structured light scanning
  - X-ray and CT scan
  - Microscopy
  - Density
  - Mechanical testing
- The team identified key factors and hypotheses which may explain observed differences in mechanical properties between flight and ground samples
- Plans are being developed to evaluate hypotheses and generate needed additional mechanical properties data through FY16 prints on ISS
- Lessons Learned have been incorporated into the next generation 3D Printer for ISS – Additive Manufacturing Facility (AMF) by Made In Space

JOURNEY TO MARS



HUBBLE

INTERNATIONAL SPACE STATION

SPACE LAUNCH SYSTEM (SLS)

ORBITERS

LANDERS

SCIENCE

EXPLORATION

TECHNOLOGY

PHOBOS

DEIMOS

ORION

SOLAR ELECTRIC PROPULSION

ASTEROID REDIRECT MISSION

IN-SPACE HABITAT

MARS TRANSFER SPACECRAFT

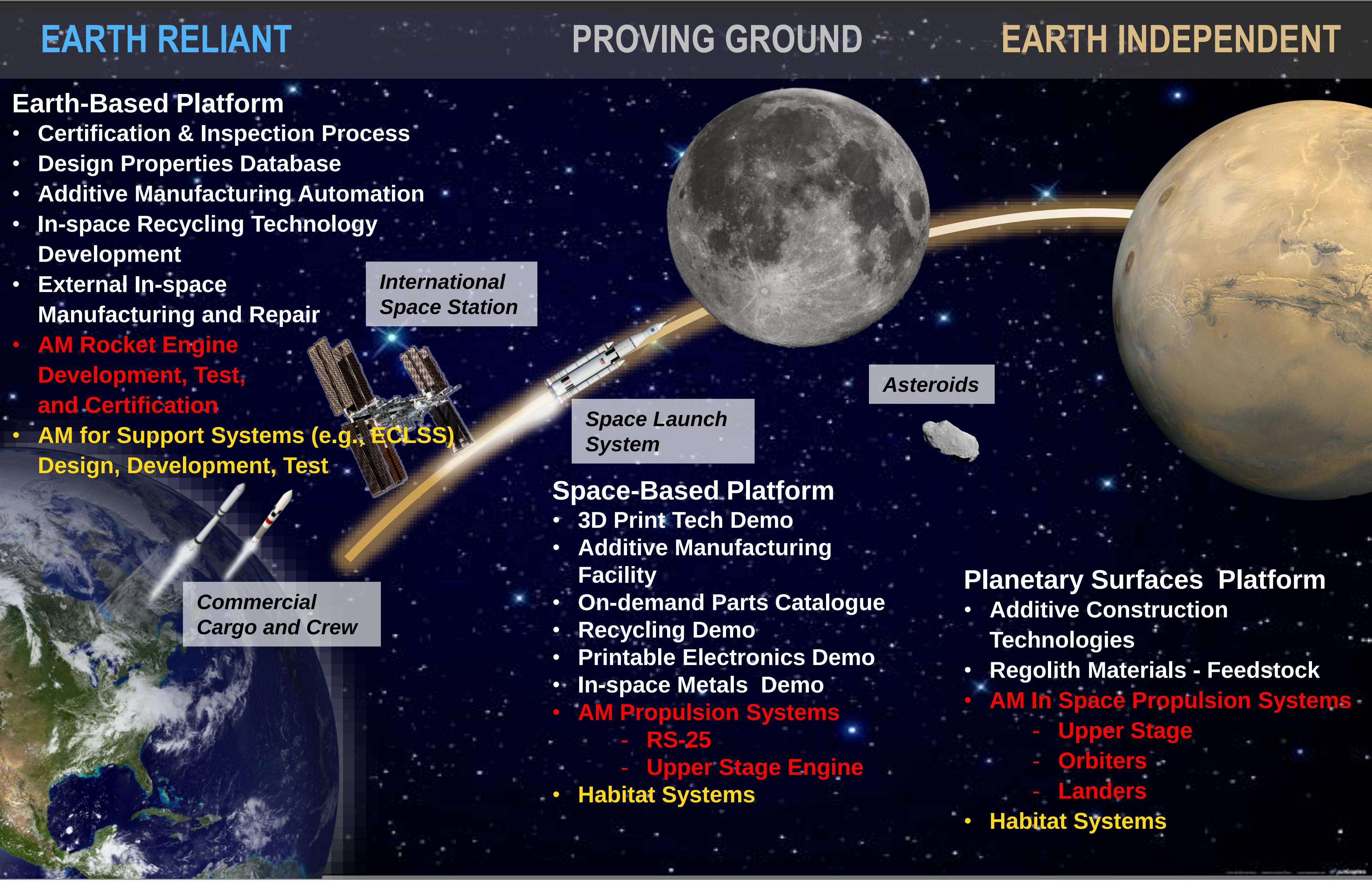
COMMERCIAL CARGO AND CREW

MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT

MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS
PROVING GROUND

MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

Additive Manufacturing Path to Exploration



Earth-Based Platform

- Certification & Inspection Process
- Design Properties Database
- Additive Manufacturing Automation
- In-space Recycling Technology Development
- External In-space Manufacturing and Repair
- AM Rocket Engine Development, Test, and Certification
- AM for Support Systems (e.g., ECLSS) Design, Development, Test

Space-Based Platform

- 3D Print Tech Demo
- Additive Manufacturing Facility
- On-demand Parts Catalogue
- Recycling Demo
- Printable Electronics Demo
- In-space Metals Demo
- AM Propulsion Systems
  - RS-25
  - Upper Stage Engine
- Habitat Systems

Planetary Surfaces Platform

- Additive Construction Technologies
- Regolith Materials - Feedstock
- AM In Space Propulsion Systems
  - Upper Stage
  - Orbiters
  - Landers
- Habitat Systems

In-Space Manufacturing Elements

Material Characterization Database Development

- Objective: Characterize microgravity effects on printed parts and resulting mechanical properties. Develop design-level database for microgravity applications.
- Phase II operations for additional on-orbit prints of engineering test articles are being planned with ISS (3D Printer and AMF)
- All datasets will be available through the MSFC Materials and Processes Technical Information System (MAPTIS)

On-demand ISM Utilization Catalogue Development

- Objective: Develop a catalogue of approved parts for in-space manufacturing and utilization
- Joint effort between MSFC AM M&P experts, space system designers, and JSC ISS Crew Tools Office
- Continuing to document and socialize on-orbit printing process with users and ISS Program (safety, human factors, etc.). ISM in the process of developing V&V/Quality Control/Certification process and process for Candidate Part inclusion.

Compression Testing of Mechanical Flight Sample 7/21/15

OGS AAA Inlet Adaptor

Freedom 360 Virtual Reality Rig

In-Space Manufacturing Elements

AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space

- Commercial printer for use on ISS
- Incorporates lessons learned from 3D Printer ISS Tech Demo
- Expanded materials capabilities: ABS, ULTEM, PEEK
- Anticipated launch late CY2015

In-space Recycler ISS Tech Demonstration Development (SBIR 2014)

- Objective: Recycle 3D printed parts into feedstock to help close logistics loop
- Phase I recycler developments completed by Made In Space and Tethers Unlimited
- Phase II SBIR (2014) awarded to Tethers Unlimited for the In-space Recycler for proposed ISS Technology Demonstration in FY2017

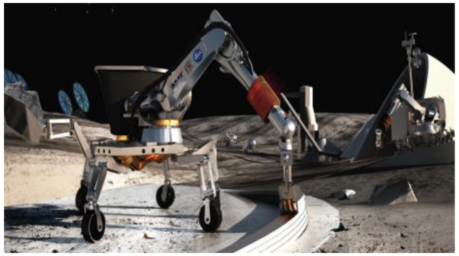
Launch Packaging Recycling Phase I SBIR (2015)

- Objective: Recycle launch packaging materials into feedstock to help close logistics loop (3 proposals selected for award)

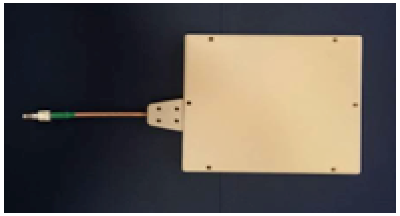
In-space Printable Electronics Technology Development

- Collaborating with Xerox Palo Alto Research Center (PARC), NASA Ames Research Center, and AMRDEC
- Roadmap developed targeting ISS technology demonstration
- Printing a Radio Frequency Identification (RFID) antenna for assessment on the RFID Enabled Autonomous Logistics Management Tech Demo
- Additive ultracapacitors have been developed, tested, & patented utilizing MSFC Innovation Funds

Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo



Concept of ATHLETE-based autonomous additive construction system on extraterrestrial surface



Printable RFID Antennae

Printed Ultra-capacitor sample cell

NASA/DARPA In-Space Manufacturing and Repair Broad Agency Announcement (BAA) FY16 Implementation

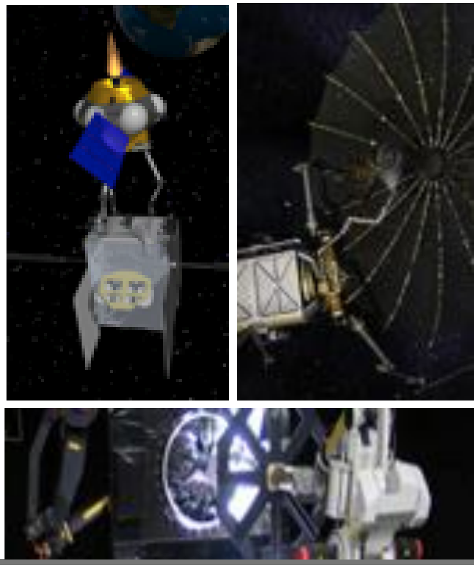
Description and Objectives

- Explore the technologies available today that could be utilized for a future in-space demonstration
- Targeted Areas of Interest for an External In-space Manufacturing & Repair Technology Flight Demo include:
  - Additive Manufacturing Technologies
  - Printable Electronics
  - Autonomous & Remote Ops
  - Inspection - Manufacturing context, situational awareness and metrology
  - Ionic Liquids Extraction & Utilization

Approach

- Two types of proposals solicited
  - External In-Space Systems Demo
  - Subsystems technology (ground based) demos – precursor to follow-on flight opportunity
- Selection made in 2016
- One or two year awarded project based on proposals and funds available

NASA In-Space Manufacturing



DARPA Phoenix/SUMO/FREND

Science & Technology Office

In-space Manufacturing Exploration Technology Development Roadmap

Earth-based

Ground Analogs

- **Multiple FDM Zero-G parabolic flights (1999-2013)**
- **System Studies & ground Tests for Multiple Materials & Technologies**
- **Verification & Cert. Process development**
- **Material & Printer Characterization Database**
- **Autonomous Process Dev.**
- ***Additive Construction: Simulant Dev. &Ground***

Demos: Ground & ISS

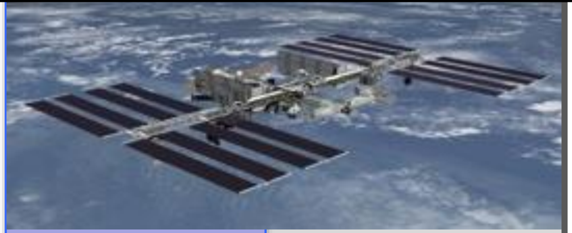
Plastic Printing Demo

Mat. Char.

3D Print Tech Demo

2014

- **In-space:3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **AF/NASA Space-based Additive NRC Study**
- **ISRU Phase II SBIRs**
- **Ionic Liquids**
- **Printable Electronics**



Recycler

Utilization Testing

AMF

2015 - 2017

- ***3D Print Demo ABS Ops***
- ***Add. Mfctr. Facility Ultem Ops (AMF)***
- ***In-space***
- ***Utilization Catalogue Part Cert & Testing***
- ***Recycler Demo***
- ***NASA/DARPA External In-space BAA Demo***
- ***In-space Material Database***
- ***Future Engineer STEM Challenge(s)***

Metal Printing

Fab Lab

Self-repair/ replicate

Digital Mftr.

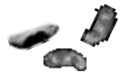
External In-space Mftr

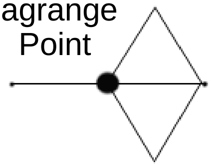
2018 - 2024

ISS: "Fab Lab" *Utilization/Facility Focus*

- In-space Recycler Demo
- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Embedded Electronics Tech Demo
- Synthetic Biology Demo
- Metal Demo Options
- ***ACME Ground Demos***

Exploration





2025-35

Lunar, Lagrange FabLabs

- Initial Robotic/Remote Missions
- ***Provision feedstock***
- ***Evolve to utilizing in situ materials (natural resources, synthetic biology)***
- ***Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. "living off the land"***
- Autonomous final milling to specification

2035+

Planetary Surfaces Points Fab

- Transport vehicle and sites would need Fab capability
- ***Additive Construction & Repair of large structures***

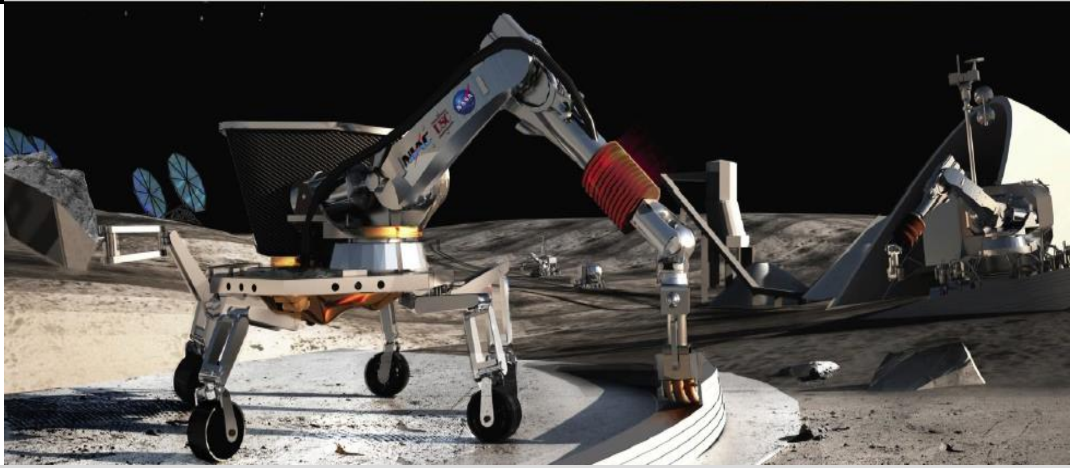
Mars Multi-Material Fab Lab

- ***Provision & Utilize in situ resources for feedstock***
- ***FabLab: Provides on-demand manufacturing of structures, electronics, & parts utilizing in-situ and ex-situ (renewable) resources.*** Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment at remote destinations.

**** Green text indicates ISM/ISRU collaboration***

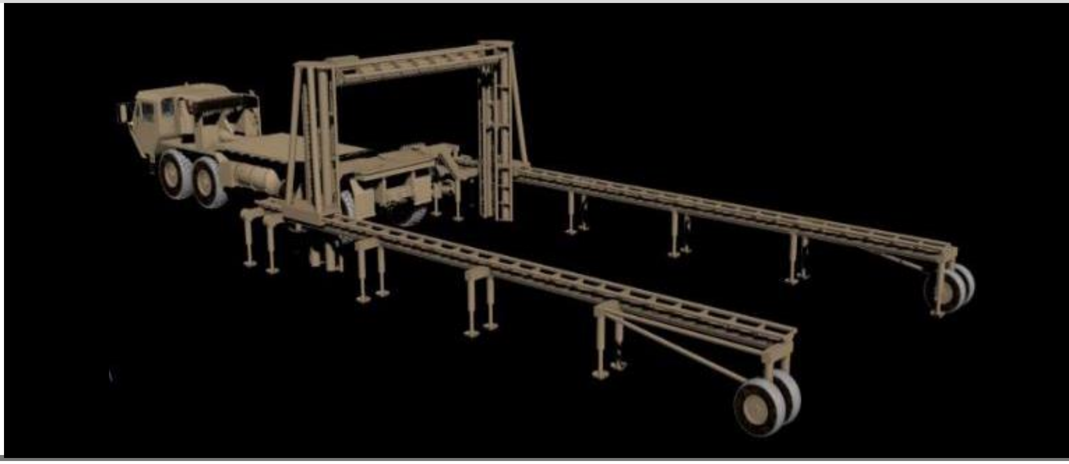
ISS Serves as a Key Exploration Test-bed for the Required Technology Maturation & Demonstrations

Additive Construction with Mobile Emplacement (ACME)



Vision: Capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials.

Automated Construction of Expeditionary Structures (ACES)



Expeditionary Structure Needs

- **NASA needs an autonomous construction capability utilizing in-situ resources for the fabrication of planetary surface infrastructure, including habitats, garages, roads, and berms that will:**
  - Reduce mass of materials that must be transported to the space destination by a factor of 2,000:1
  - Improve motion control accuracy by an order of magnitude to deposit layers consistently during construction
  - Protect landed assets & crews from the local environment (temperature, radiation environment, vacuum, micro-meteorites, dust, rocket plume ejecta)

- **The Army needs to fabricate structures in 24 hours or less that:**
  - Reduce required personnel from 8 to 3
  - Reduce weight of material to be shipped into theater by 50%
  - Are immune to weather and termites
  - Can survive in theater longer than 6 months
  - Protect troops living and working inside
  - Are adaptable to the appearance and function of local buildings

ACME/ACES Project and Team

- **Technical Description:**
  - An integrated mobility system for 3D printing on a structure scale using contour crafting technology will be developed using an iterative maturation approach
  - Robotic arm and gantry systems will be investigated for optimum use of contour crafting technology, continuous 3D printing capability, and required positioning precision

- **Partner Roles and Responsibilities:**
  - ERDC CERL
    - ACES requirements
    - Materials
    - Structural analysis, energy analysis
    - Robotic control systems
    - Gantry design and fabrication
    - Gantry system integration and testing
  - NASA MSFC
    - Planetary materials and simulants
    - Binder materials development, storage, delivery system
    - Continuous feed materials delivery system
    - Tool path development
    - Robotic arm testing
    - Radiation protection
    - System testing
  - NASA KSC
    - Feedstock characterization, excavation, processing, transport, and storage
    - Dry goods delivery system
    - Excavation and handling testing
  - NASA JPL
    - Robotic arm control systems
    - ATHLETE testing
  - Contour Crafting Corporation (CCC) (Prof. Behrokh Khoshnevis)
    - Nozzle design, development, and fabrication
    - Feed system consultant

ACME Status

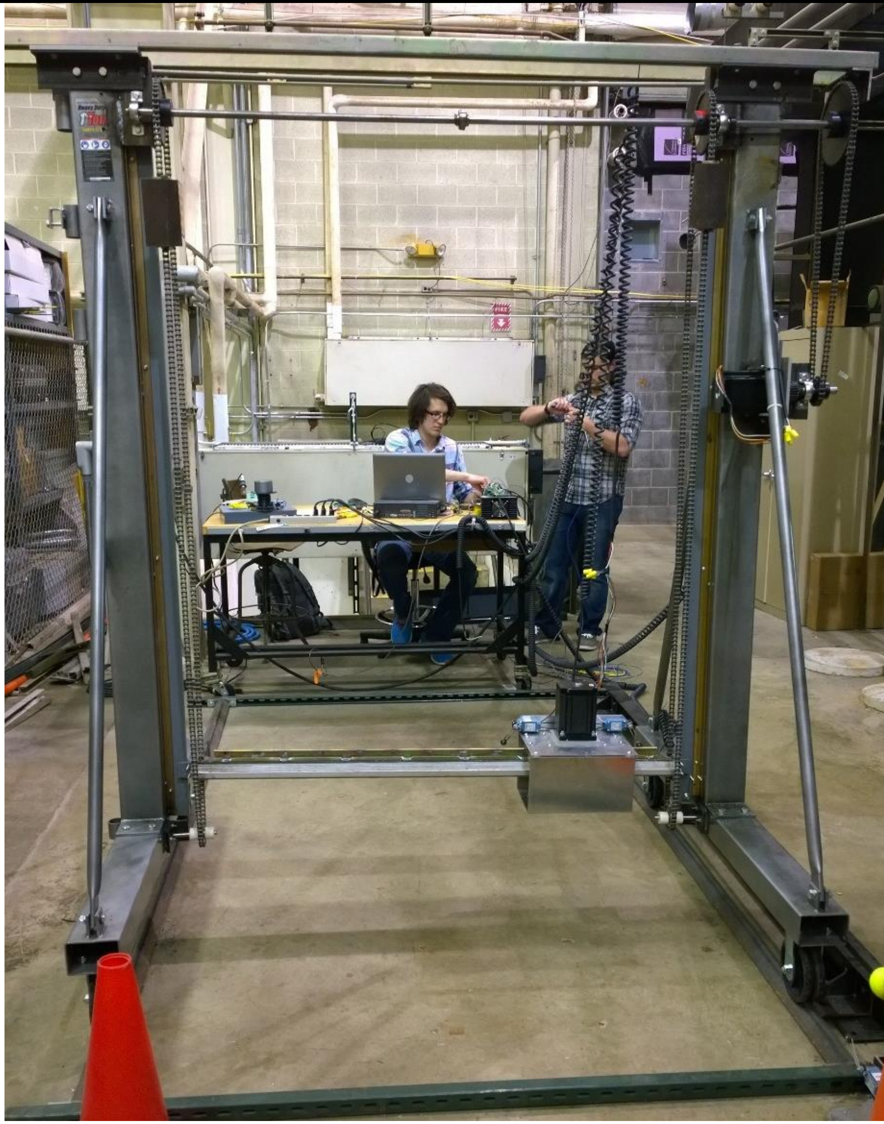
- **ACME 1 development and testing requirements completed**
  - Assessed and selected Martian simulant
  - Assessed various binder materials for concrete mixtures
  - Completed print trials using various concrete material mixtures
  - Printed 10”h x 2.25”w x 36”l wall section
  - Completed tool path development and control system enabling curved wall segment printing (18”rad x 56”l x 9”h)
- **ACME 2 transition in progress**
  - Binder storage and delivery system and CFDMS (late March)
  - CCC ACME 2 nozzle (late February)
  - Robot arm transition in Spring 16
  - Trial prints in Summer 16

Construction of a straight wall segment using martian simulant concrete, composed of Martian simulant, Portland cement, and stucco mix

Construction of a curved wall segment using Martian simulant concrete (completed 11/4/15)

ACES Status

- **ACES Prototype 1 development and testing requirements completed**
  - – Print trial concrete material mixtures
  - – Use selected mixture to print 8” X 4’ X 4’ wall section
- **ACES 2 moving towards Spring 16 integration and trial prints**
  - – MSFC binder storage and delivery system and CFDMS (late March)
  - – KSC dry goods storage and delivery system (late March)
  - – CCC nozzle (late February)
  - – B Hut trial expected in Summer 16



ACES Prototype 1

ACES Status

B-Hut Development and Test Area at ERDC-CERL

ACES 2 Gantry Concrete Mixer and Pump

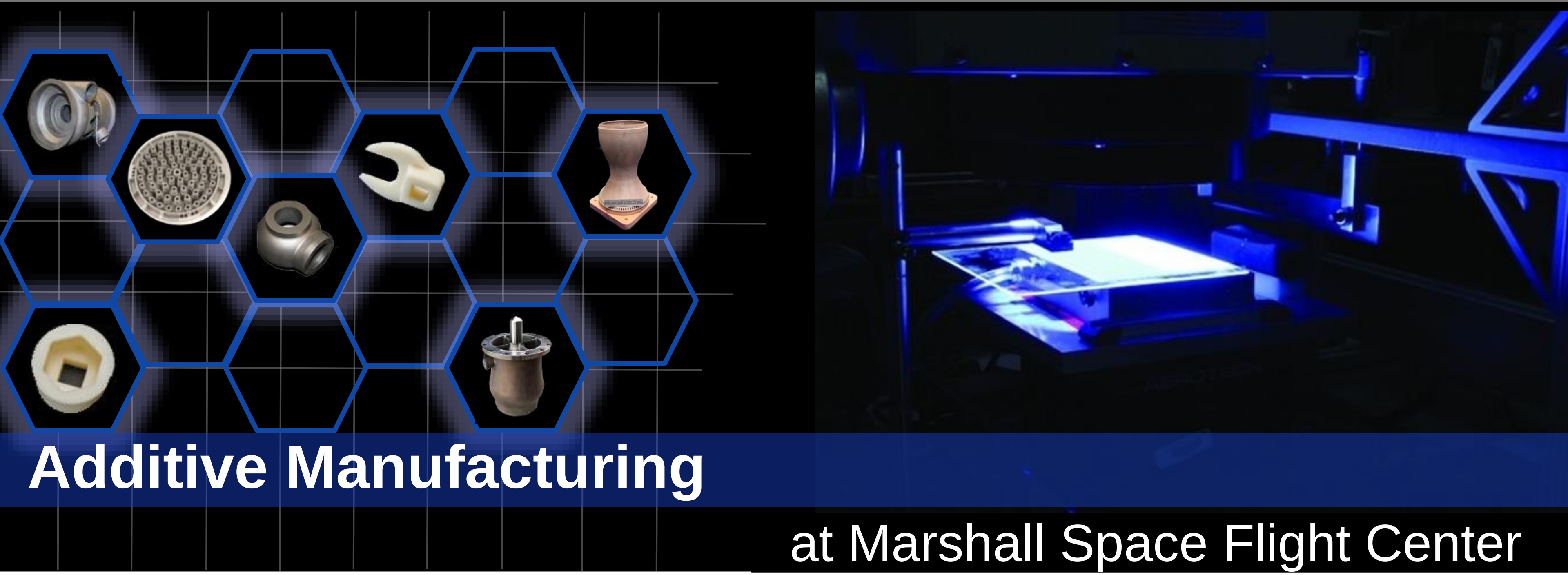
ACES End State

- Capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials
- Flexibility in design, application, and transfer of constructed shelters, tailored to environment - aesthetically and functionally
- 500 ft2 SEA-hut equivalent
- Develop automated capability to produce on-site beams, trusses, and vaults
- Understand performance characteristics of structures and components constructed using ACES (structural, energy, protection)
- Computational models for design, structural, energy, protection analysis
- Guidance for use of readily-available onsite materials (i.e., cement, adobe, etc.)
- Guidance to adjust mechanical material properties to be suitable for ACES

USACE Video

Summary

- **In-space manufacturing is a critical capability needed to support NASA's deep space exploration missions**
  - Increase in reliability
  - Reduction in logistics burden (make it or take it)
  - Recycling capabilities
  - Flexibility in design
- **NASA has taken the first step towards in-space manufacturing capability by successfully demonstrating 3D print technology on ISS**
- **The journey through development and proving ground trials is a long one**
  - Foundational technologies are yet to be demonstrated
  - Design for repair culture needs to be embraced
  - Applications need to be validated
- **Additive construction offers significant potential for expeditionary structures for the Army and NASA and, in addition, commercial, humanitarian assistance and disaster relief possibilities. Excellent opportunity for demonstration of public/private partnerships.**

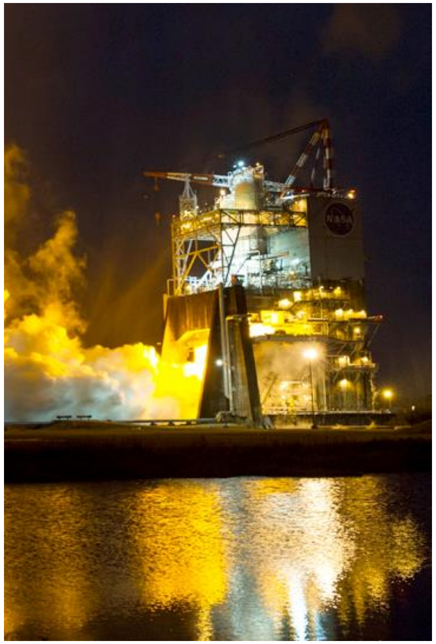


BACK UP

Engineering and Quality Standard for (Human-Rated) Additively Manufactured Space Flight Hardware

AM in the Human Exploration and Operations Portfolio

Exploration Systems Development
ORION and SLS



Commercial Crew Program
DRAGON V2

Requirement choices dictate how we embrace, foster, and protect the technology and its opportunities

Requirements Approach

- **Typical scenario used to control critical processes**
  - Broad Agency-level standards provide requirements
    - NASA-STD-6016 Materials
    - NASA-STD-5012 Propulsion Structures
    - NASA-STD-5019 Fracture Control
  - Which call process or quality standard controls product, for example:
    - AWS D17.1 Fusion Welding for Aerospace Applications
    - SAE AMS 2175 Classification and Inspection of Castings
    - SAE AMS 4985 Ti-6-4 Investment Castings
  - Which call considerable collections of “Applicable Documents”
- **Additive manufacturing standards currently very limited**
  - Lacking standardization is a universal, industry-wide issue, not just NASA
  - Mainly ASTM, Committee F42 on Additive Manufacturing
    - F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718)with Powder Bed Fusion
    - F2924 for Ti-6-4, F3001 for Ti-6-4ELI, F3056 for In625
  - Other Standards organizations in planning
    - SAE AMS, AWS
- **NASA required to develop government requirements to balance AM opportunities and risks**

Engineering and Quality Standard for AM Spaceflight Hardware

National Aeronautics and
Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard
for Additively Manufactured
Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

Document Contents

- Governing Standards
- Design for AM
- **Part Classification**
- Structural Assessment
- Fracture Control
- Qualification Testing
- **Material Properties**
- **Process Controls**
  - ***Metallurgical Process Control***
  - ***Part Process Control***
  - ***Equipment Vendor Controls***
  - ***Design and Build Vendor Controls***

Key Knowledge Gaps and Risks

- **Available standards will not mitigate AM part risk to a level equivalent to other processes for some time to come!**
- **Known Unknowns needing investment:**
  - Unknown failure modes :: limited process history
  - Open loop process, needs closure or meaningful feedback
  - Feedstock specifications and controls
  - Thermal processing
  - Process parameter sensitivity
  - Mechanical properties
  - Part Cleaning
  - Welding of AM materials
  - AM Surface improvement strategies
  - NDE of complex AM parts
  - Electronic model data controls
  - Equipment faults, modes of failure
  - Machine calibration / maintenance
  - Vendor quality approvals

Knowledge gaps exist in the basic understanding of AM Materials and Processes, creating potential for risk to certification of critical AM Hardware.

Additive Manufacturing Structural Integrity Initiative

Lead Center in Blue

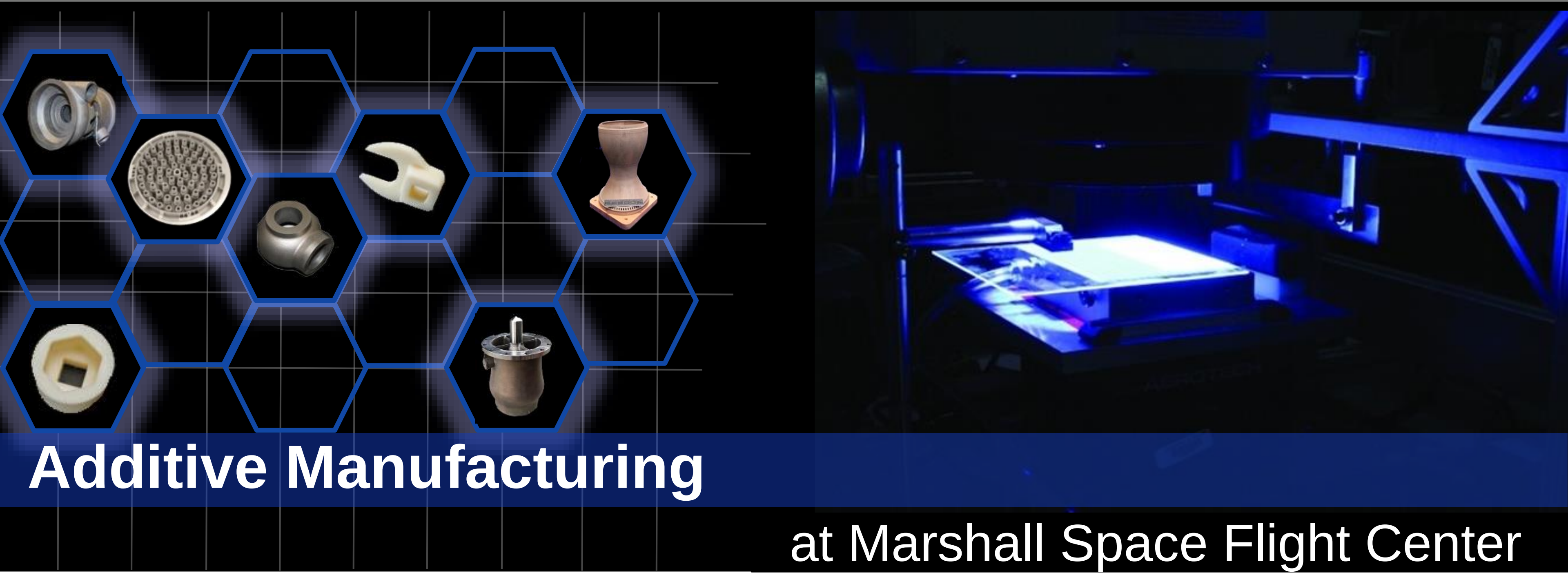
Build the standard level of information on AM powder bed fusion processes that is required for certification of any new critical process used for aerospace applications. Better understanding of controlling process parameters and process failure modes will be achieved through completion of this study.

- Certification Requirements – **MSFC**/JSC/KSC (committee) **Objective**: Develop an Agency-wide accepted practice for the certification of AM processes for aerospace hardware.

1. Powder Influence – **GRC**/LaRC/MSFC **Objective**: Understand how basic powder feedstock characteristics influence a PBF part's physical, mechanical, and surface properties.
2. Build Interactions – **MSFC**/GRC/LaRC **Objective**: Use DOEs to understand how basic AM build factors influence part properties. (Answers how we declare the PBF process acceptable & in-control; e.g. microstructural criteria, density criteria, laser/power effects, process FMEA, mitigation of process failure modes)
3. Characteristic Defects – **LaRC**/GRC/MSFC **Objective**: Identify, catalog, and reproduce defects characteristic of the AM process.
4. Thermal Processing – **GRC**/LaRC/MSFC **Objective**: Establish an understanding of how post-build thermal treatments affect build quality, microstructural evolution, and mechanical properties.
5. Surface Improvement – **LaRC**/MSFC **Objective**: Understand how as-built and improved AM surface texture influence part performance and fatigue life.
6. Characterization in Environment – **MSFC**/GRC/LaRC **Objective**: Understand mechanical behavior of AM Inconel 718 in representative aerospace environments.
7. Design Engineering – **MSFC** **Objective:** Demonstrate the certification process for AM propulsion components. Increase TRL of propulsion components through testing in operational environment.

Related Task: NASA NDE Working Group Additive Manufacturing Proposed Tasks – Various Centers **Objective**: Assessment of NDE Capability for AM parts and creation of NDE standards and models. (sponsored by OSMA)

Project designed to leverage Centers' critical skills, knowledge, and expertise.



BACK UP

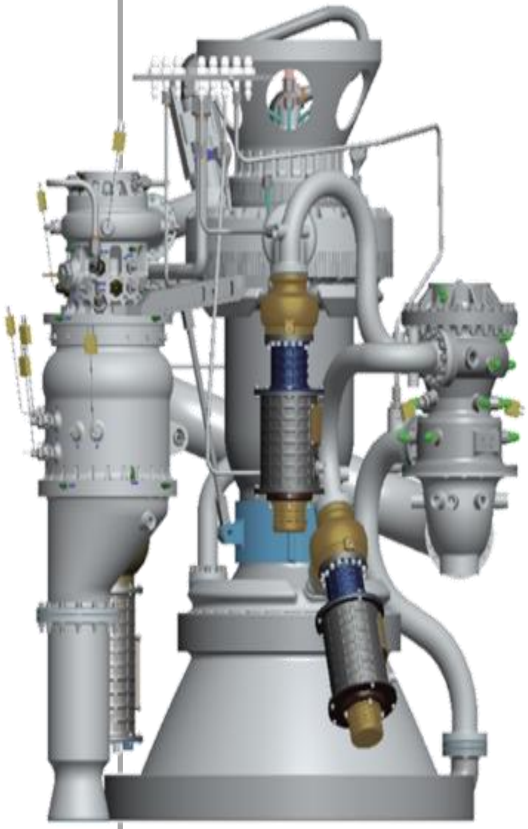
Advanced Manufacturing Demonstration: Liquid Propulsion System

Transforming Liquid Propulsion Systems DDT&E with AM

Additive manufacturing related

Project Objectives

- **Reduce the cost and schedule required for new engine development and demonstrate it through a complete development cycle.**
  - Prototype an engine in less than 2.5 years.
  - Use additive manufacturing to reduce part cost, fabrication time, and overall part count.
  - Adopt Lean Development approach.
    - Focus on fundamental/quick turn analysis to reduce labor time and cost and move to first development unit
    - Get hardware into test fast so that test data can be used to influence/refine the design
- **Advance the TRL of additive manufactured parts through component and engine testing.**
- **Develop a cost-effective prototype engine whose basic design can be used as the first development unit for an in-space propulsion class engine.**



Strategic Vision for Future AM Engine Systems

Defining the Development Philosophy of the Future

- **Integrating Design with Manufacturing**
- **3D Design Models and Simulations Increase Producibility**
- **Transforming Manual to Automated Manufacturing**
- **Dramatic Reduction in Design Development, Test and Evaluation (DDT&E) Cycles**

Building Foundational Industrial Base

DIRECTEDMFG AS9100B Certified

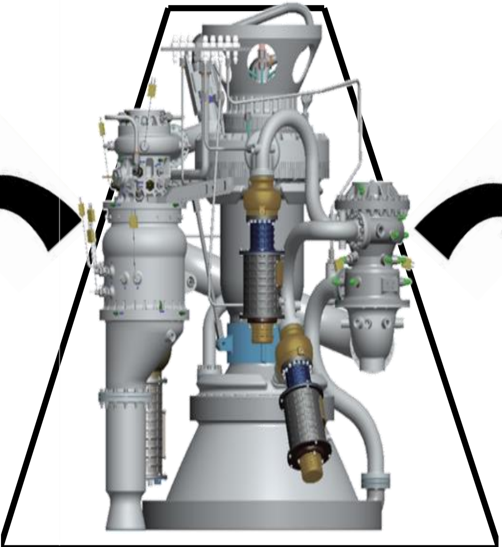
INCODEMA SHAPING THE FUTURE

MORRIS TECHNOLOGIES Precision. Innovation. Expertise.

SOLID CONCEPTS®

LINEAR MOLD & ENGINEERING

RPM INNOVATIONS, INC.



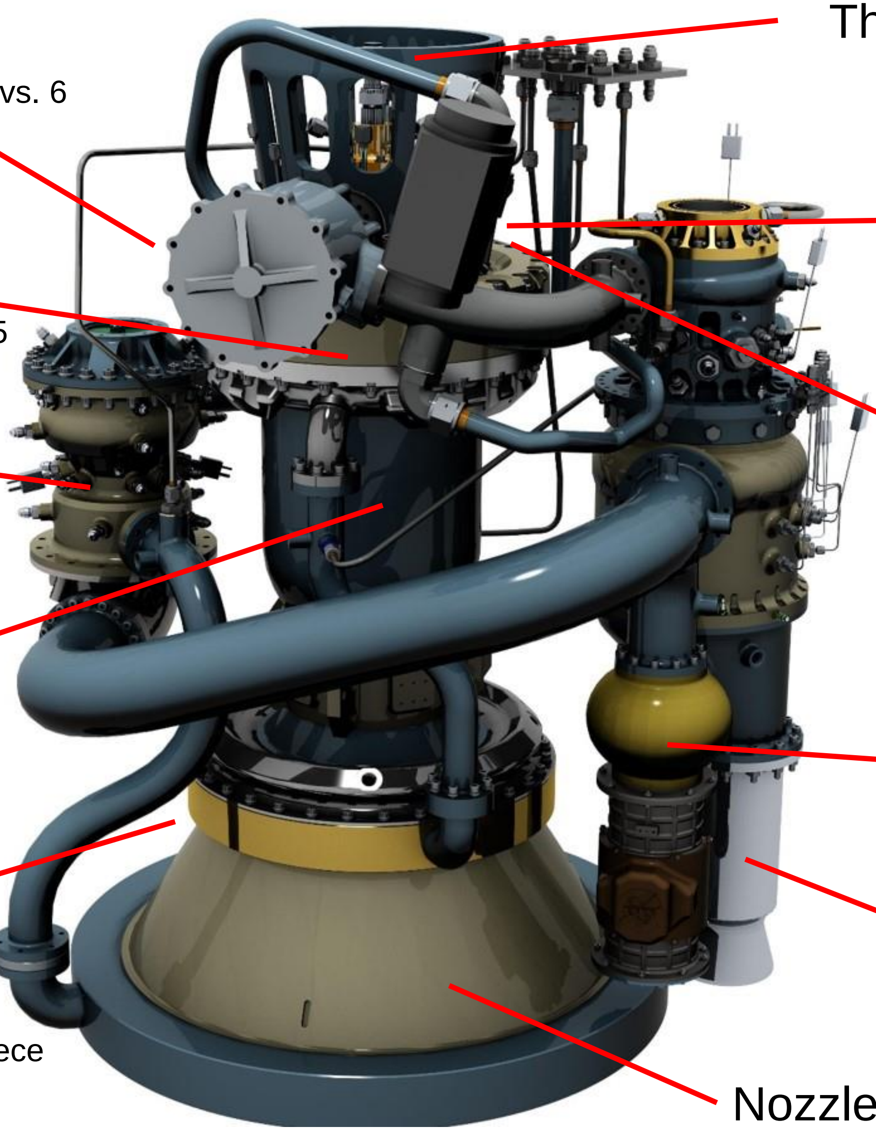
Bridging the gap between the present and future projects that are coming

Transferring "Open Rights" SLM Material Property Data & Technology to U.S. Industry

Building Experience "Smart Buyer" to enable Commercial Partners

Enabling & Developing Revolutionary Technology

Expected Reduction in Parts Count for Major Hardware



Thrust Structure

MOV
Part Count (Approx): 1 vs. 6

MFV (Hidden)
Part Count (Approx): 1 vs. 5

Injector
Part Count (Approx): 6 vs. 255

Mixer (Hidden)
Part Count: 2 vs. 8

FTP
Part Count (Approx): 22 vs. 40

MCC

OTBV
Part Count (Approx): 1 vs. 5

CCV (Hidden)
Part Count (Approx): 1 vs. 5

Turbine Discharge Duct

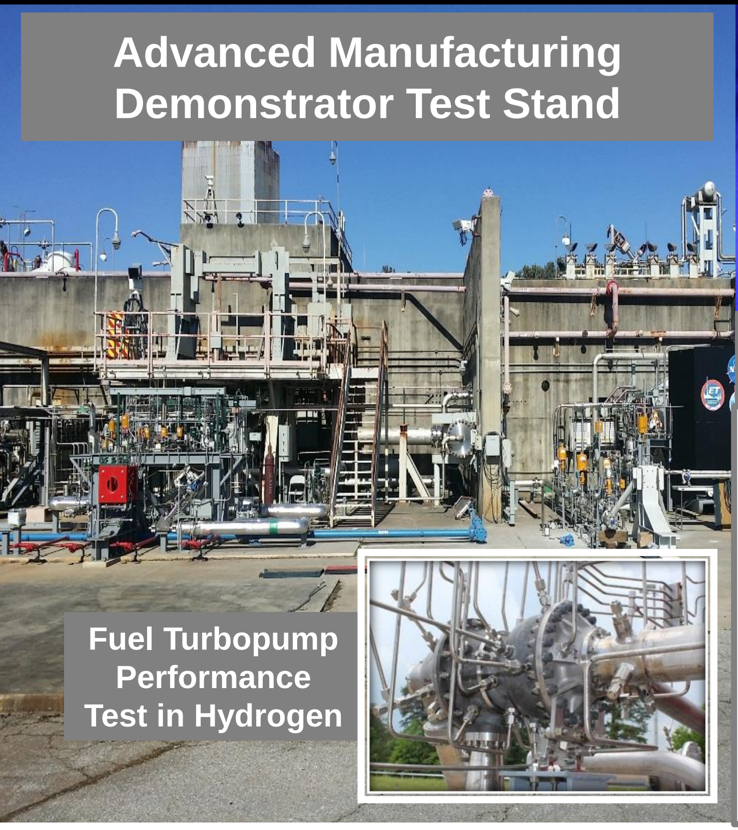
Nozzle

Note: Parts count represent major piece parts, and do not include bolts, nuts, washers, etc.

Game-Changing Aspects of Prototype Additive Engine

State of the Art for Typical Engine Developments		Prototype Additive Engine
• DDT&E Time – 7-10 years	***1/2 Development Lead Time***	• DDT&E Time – 2 - 4 years
• Hardware Lead Times – 3 - 6 Years	***1/6th Production Time***	• Hardware Lead Times – 6 Months
• Testing – Late in the DDT&E cycle		• Testing – Early in the DDT&E cycle
• Engine Cost – $20 - $50 Million	***1/10th Reoccurring Cost***	• Prototype Cost – $3 - 5 Million

Hardware and Testing Accomplishments



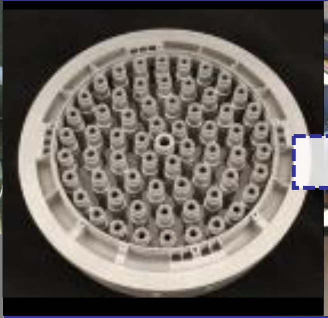
Advanced Manufacturing Demonstrator Test Stand

Fuel Turbopump Performance Test in Hydrogen

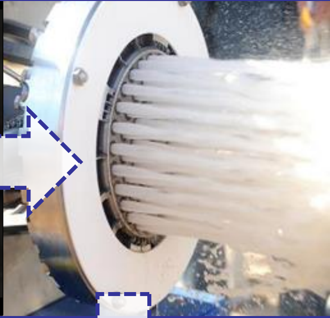
LCUSP MCC Liner

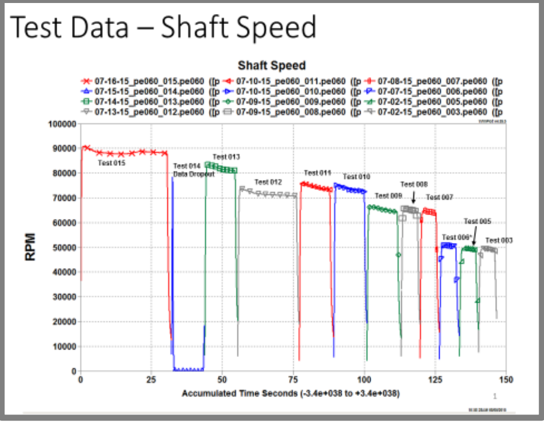
Main Fuel Valve Cryo Test

Fuel Scale Injector Swirl Elements



Full Scale Injector Water Flow





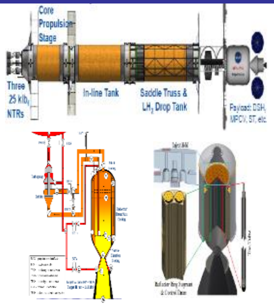
Test Data – Shaft Speed

Sub-scale Injector Test

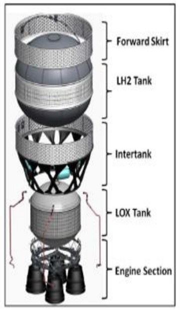
Advanced Manufacturing Demonstrator (AMD)

Investment directly benefits prototype engine development and indirectly enables and facilitates technology across multiple current and future activities for NASA and industry.

Methane Lander



Nuclear Thermal Propulsion (NTP)



Exploration Upper Stage (EUS)